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Circular Capacitance Micromachined Ultrasonic Transducer

Shailendra Kumar Tiwari[*], B.S. Satyanarayana[**], A. Gopalkrishna Pai[*], and Kunal K. Trivedi[***]

[*]Manipal Institute of Technology, Manipal-576 104
[**]Environment, Science & Technology Office, US Embassy, New Delhi-110 021
[***]Bigtec Private Limited, Bangalore-560 082
E-mail: electshail@yahoo.com

ABSTRACT

Capacitance micromachined ultrasonic transducers (CMUTs) have become an attractive alternative to the piezoelectric transducers, especially in air-coupled nondestructive evaluation (NDE) and ultrasound medical imaging flow metering, micro/nanoelectronics, and industrial cleaning, etc. These are similar to other capacitance transducers as these employ a vibrating membrane to send and receive ultrasound in air and water. This paper describes the theory and design of a circular micromachined ultrasonic transducer which could lead to a CMUT with many advantages, including less loading effect. The software programs (Intellisuite 8.2 and MATLAB 7.0) were used to model a single cell of CMUT. The simulations-based studies of the critical parameters like collapse voltage and snapback voltage, which influence the operation of the CMUTs to a large extent, has been discussed. Small signal equivalent circuit model for the circular CMUT has been discussed and the program (SPICE) has been used for the simulation of the small signal equivalent circuit.

Keywords: Central frequency, capacitance micromachined ultrasonic transducer, CMUTs, collapse voltage, mechanical impedance, snapback voltage, transducer, small signal equivalent circuit.

1. INTRODUCTION

Ultrasound is widely used in medical imaging and nondestructive evaluation. It is also applied in gas flow metering, industrial cleaning procedures, soldering, position sensing, wafer temperature sensing, etc[1]. Currently, the vast majority of ultrasound transducers are fabricated using piezoelectric crystals and composites. Some conventional ultrasonic transducers use piezoelectric material PZT (i.e., lead zirconate titanate) as a piezoelectric device that converts the electrical signal to ultrasound waves, but piezoelectric transducers are problematic in fluid-coupled application because of impedance mismatch between the piezoelectric and fluid of interest.

In air, for example, the generation of ultrasound is challenging because the acoustic impedance of the air (400 kg/m^{2}s) is many order of magnitude smaller than the impedance of the piezoelectric materials commonly used to excite ultrasonic vibrations[1] (approximately 30 x 10^6 kg/m^{2}s). To improve efficiency, a matching layer is usually placed between the piezoelectric material and air[2].

Another disadvantage of piezoelectric devices over electrostatic transducers is their temperature sensitivity. The PZT-based transducers are very sensitive to temperature and these can only be used at near room temperature but electrostatic transducers are only limited by melting point and the different thermal expansions of the material used[3]. As piezoelectric transducers have drawbacks it motivates micromachined approach to transducer design. Capacitive micromachined ultrasonic transducers (CMUTs) operate on a capacitive principle of ultrasonic transduction that has several advantages over the more traditional piezoelectric methods, especially when used in air-coupled applications[2]. The membrane material thickness has an impact on the performance of the CMUTs. In this paper, the influence of the mechanical impedance of the membrane, collapse voltage, and the central frequency for different thickness of poly-silicon membrane on the performance of CMUT is discussed. Figure 1 shows the schematic of a single cell CMUT.

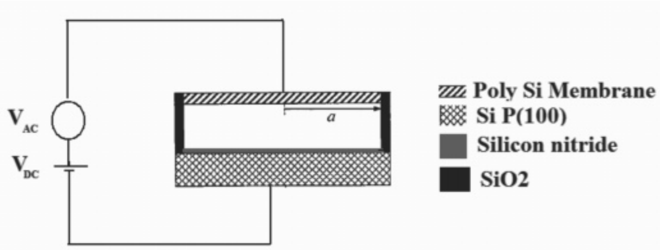

Figure 1. Schematic of one element of CMUT.

To generate acoustic waves, the membrane is driven in oscillation mode, superimposing on the polarisation voltage V_{dc} an alternating component V_{ac}, which varies the electrostatic force generated by the static voltage V_{dc}. The polarisation voltage V_{dc} is key to transmission as it causes the deflection of the top electrode due to electrostatic force towards the bottom electrode, a quadratic relationship exists between force and applied voltage.

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An alternating voltage applied to the CMUT without polarisation voltage would cause attraction of the membrane twice in a single cycle forcing the membrane to oscillate at double the frequency[4]. If the membrane is biased appropriately and subjected to ultrasonic waves at resonance frequencies, significant detection current will be generated[5].

2. RESONANCE FREQUENCY

In a CMUT, a membrane is actuated by a time varying input voltage and the vibration of the membrane generates ultrasound waves in the medium ahead of it. The natural frequency of the membrane is known as the central frequency or the resonance frequency of the transducer.

$$f = \frac{0.47 l_t}{a^2}\sqrt{\frac{Y_0}{\rho(1-\sigma^2)}}$$

where f is the resonance frequency, l_t = thickness of the membrane, a= radius of the device, ρ= density of the membrane material, σ = Poison's ratio, Y_0= Young's modulus of the membrane material.

3. MECHANICAL IMPEDANCE OF SINGLE CMUT CELL

A circular membrane of a radius a operating in air has benn considered. The poly-silicon membrane has Young's modulus of Y_0 and a Poisson's ratio σ. In addition, membrane is in tension T in units N/m^2. The differential equation governing the normal displacement $x(r)$ of the membrane can be written as[2,6].

$$\frac{(Y_0+T)l_t^3}{12(1-\sigma^2)}\nabla^4 x(r) - l_t T\nabla^2 x(r) - P - l_t\rho\frac{d^2x(r)}{dt^2} = 0 \quad (1)$$

where, l_t is the thickness of the membrane and P is the external uniform pressure applied to the membrane. The equation is derived from an energy formulation and the critical sumption is that the tension generated by a displacement x is small compared to the tension T. Assuming a harmonic extension at an angular frequency ù, Eqn (1) is known to have solution of the form

$$\begin{aligned} x(r) &= AJ_0(k_1 r) + BJ_0(k_2 r) + CK_0(k_1 r) \\ &\quad + DK_0(k_2 r) - P/(\omega^2\rho l_t) \end{aligned} \quad (2)$$

where, A, B, C and D are the arbitrary constants, $J_0()$ is the zeroth order Bessel's function of first kind, and $K_0()$ is the zeroth order Bessel's function of second kind. It is deduced that C = 0 and D = 0 because of Bessel's function of second kind is infinite at $r=0$ which is not physical, if Eqn (2) is used to substitute for $x(r)$ in Eqn (1), it is found that k_1 and k_2 must satisfy the characteristics Eqn (2).

$$\frac{(Y_0+T)l_t^2}{12(1-\sigma^2)}k_1^4 + \frac{T}{\sigma}k_1^2 - \omega^2 = 0 \quad (3)$$

$$\frac{(Y_0+T)l_t^2}{12(1-\sigma^2)}k_2^4 + \frac{T}{\sigma}k_2^2 - \omega^2 = 0 \quad (4)$$

Following Mason's notation, it is defined[7]

$$c = \frac{(Y_0+T)l_t^2}{12(1-\sigma^2)}, \text{ and } d = \frac{T}{\rho}$$

The quadratic formula then gives the solution

$$k_1 = \sqrt{\frac{\sqrt{d^2+4c\omega^2}-d}{2c}} \quad (5)$$

and $$k_2 = j\sqrt{\frac{\sqrt{d^2+4c\omega^2}+d}{2c}} \quad (6)$$

To determine the constants A and B, two boundary conditions are necessary. Physically reasonable boundary conditions at $r=a$ is that $x=0$, which implies that the membrane undergoes no displacement at its periphery, and $(d/dr)\, x=0$, which implies that membrane is perfectly flat at its periphery. Both conditions amount to stating that membrane is perfectly bonded to an infinitely rigid substrate. Using these conditions, the constant A and B are determined and the final displacement of the membrane as[2,6]

$$x(r) = \frac{P}{\omega^2\rho l_t}\times\left[\frac{k_2J_0(k_1r)J_1(k_2a)+k_1J_0(k_2r)J_1(k_1a)}{k_2J_0(k_1a)J_1(k_2a)+k_1J_0(k_1a)J_1(k_2a)}-1\right] \quad (7)$$

Because it is assumed that for uniform pressure P, the force on the membrane is simply PS, where S is the area of the membrane. The velocity of the membrane is $u(r)$ =jù$x(r)$, and v is the lumped velocity parameter[1]

$$\nu = \frac{1}{\pi a^2}\int_0^a\int_0^{2\pi} u(r) r\, d\theta\, dr \quad (8)$$

$$\nu = \frac{jP}{\omega\rho l_t}\times\left[\frac{2(k_1^2+k_2^2)J_1(k_1a)J_1(k_2a)}{ak_1k_2(k_2J_0(k_1a)J_1(k_2a)+k_1J_1(k_1a)J_0(k_2a))}-1\right] \quad (9)$$

Mechanical impedance is defined as the ratio of pressure to velocity. Hence the mechanical impedance of the membrane[2,6], Z_m can be written as

$$Z_m = \frac{P}{\nu} \quad (10)$$

Let one considers

$$\begin{aligned} A_1 &= l_t a k_1 k_2 (k_2 J_0(k_1a)J_1(k_2a) \\ &\quad + l_t k_1 J_1(k_1a)J_0(k_2a)) \end{aligned} \quad (11)$$

$$\begin{aligned} A_2 &= a k_1 k_2 (k_2 J_0(k_1a)J_1(k_2a) \\ &\quad + k_1 J_1(k_1a)J_0(k_2a)) \end{aligned} \quad (12)$$

$$A_3 = 2(k_1^2+k_2^2)J_1(k_1a)J_1(k_2a) \quad (13)$$

$$Z_m = j\omega\rho l_t\left[\frac{A_1}{A_2-A_3}\right] \quad (14)$$

4. EQUIVALENT CIRCUIT

There are various parasitic losses, capacitances, inductances, and resistances that need to be included in

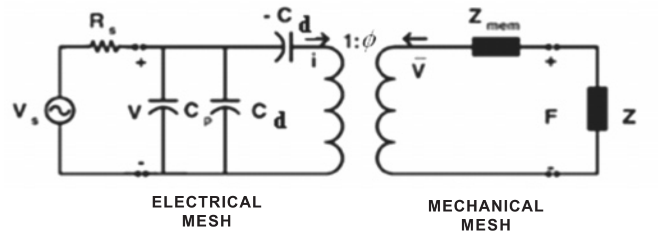


Figure 2. Small signal equivalent circuit for CMUT.

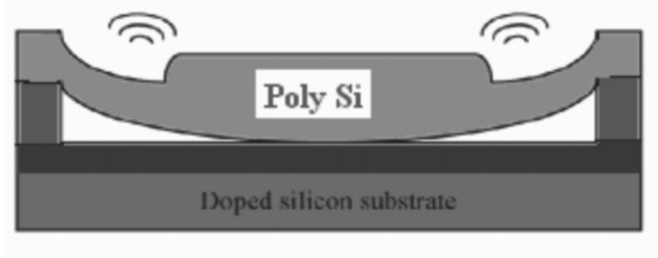


Figure 3. Collapse mode of operation.

the equivalent circuit. These arise from packaging, mechanical coupling, and resistive losses. These are taken into account as shown in equivalent circuit[5] in Fig. 2.

The force at acoustic port is given by:

$$F = SP\alpha + Z_m u' \tag{15}$$

If the current is set to zero and the acoustic port is clamped (setting $u' = 0$) then the voltage across the transformer and the force at the acoustic port is related by the transformer ratio

$$V_{AC} = \phi F = \phi\alpha SP \tag{16}$$

The transformer ratio is represented by

$$\phi = \frac{V_{AC}}{\alpha SP}$$

$$\phi = \frac{d_{eff}^2}{\alpha\varepsilon_{eff} V_{DC} S} \tag{17}$$

where, d_{eff} is the effective distance between both plate of the capacitor.

The capacitance of the active membrane element is represented by C_d

$$C_d = \alpha SP \frac{\varepsilon_{eff}}{d_{eff}} \tag{18}$$

5. COLLAPSE VOLTAGE

Collapse voltage of a CMUT is a critical parameter for employing the device at the optimum operating point. Shown in Fig. 3 is a schematic of the collapse mode operation used to used to determine the limit of applied voltage. The operating dc bias voltage determines the performance of the transducer. It also determines the operating regime at which the device is operated, such as conventional and collapse mode. As V_{dc} increased there is a point at which the electrostatic force overwhelms the spring's restoring force, and membrane collapses[2,7].

The spring constant k can be found as a ratio of pressure and volume displacement[8].

$$k = \frac{TSl_m}{\left(\frac{c}{d} - \frac{a}{2}\frac{J_0(a\sqrt{d/c})}{J_1(a\sqrt{d/c})}\sqrt{\frac{c}{d}} + \frac{a^2}{8}\right)} \tag{19}$$

If x denotes the membrane displacement the total restoring strain force is

$$F_s = kx \tag{20}$$

The electrostatic force on the membrane is given by

$$F_E = \frac{S\varepsilon^2 V^2}{2\varepsilon_0\left(l_t + \frac{\varepsilon}{\varepsilon_0}(l_a - x)\right)^2} \tag{21}$$

The voltage to keep the membrane at a certain deflection x can be found by equating F_E and F_S and solving for V.

The critical voltage at which the membrane become unstable can be determined by finding the displacement for which $\partial V / \partial x = 0$ Solving yields

$$x = \frac{1}{3}\left(l_a + \frac{\varepsilon_0}{\varepsilon} l_t\right) \tag{22}$$

and the corresponding collapse voltage is found as

$$V_{Collapse} = \sqrt{\frac{8k\left(l_a + \frac{\varepsilon_0}{\varepsilon} l_t\right)^3}{27S\varepsilon_0}} \tag{23}$$

To prevent the capacitor form shorting after the collapse, a thin insulating layer is provided at one of the electrode. After the membrane has collapsed, it will not snap back until the voltage is reduced to below $V_{collapse}$ to

$$V_{Snapback} = \sqrt{\frac{2kL_{insulator}^2 (l_a - L_{insulator})}{\varepsilon_{insulator} A}} \tag{24}$$

where k is spring constant l_a is separation between the plates of CMUT. $L_{insulator}$ is thickness of the insulator layer. S is area of the single cell CMUT, x is collapse distance.

6. RESULTS AND DISCUSSION

For NDE application, the minimum acoustic wave (AW) size that can be detected depends on the wavelength of the ultrasound waves. So the central frequency of the transducer is one of the prime factors to decide about the minimum AW size to be detected[5]. Figure 4 shows three different modes of natural frequency for different thickness of the membrane.

Figure 5 shows the relation between the frequency and the mechanical impedance for 1 μ thick circular poly-silicon membrane.

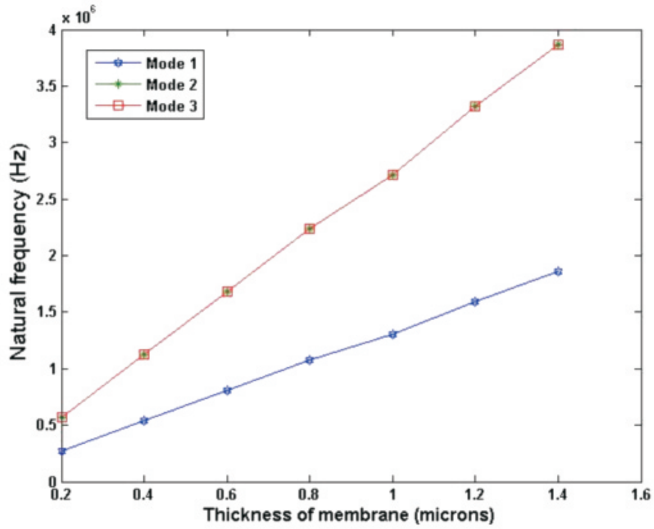


Figure 4. Natural frequency versus thickness of poly-silicon membrane.

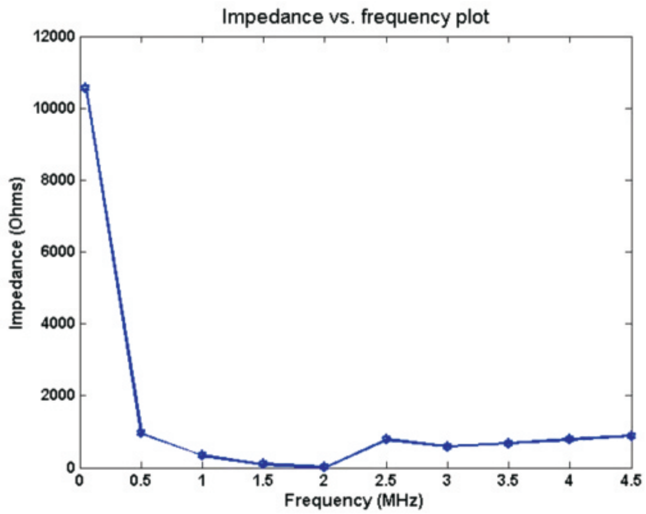


Figure 5. Mechanical impedance versus natural frequency.

The collapse voltage is used to determine the applied voltage limit of the capacitive micromachined ultrasonic transducers for proper operation of the device.

Figure 6 shows the FEM simulated result in Intellisuite 8.1 for the deflection of the membrane due to the collapse voltage, the maximum displacement 0.33 μ is achieved at the centre of the membrane.

Figure 7 gives the plot of displacement of the poly-*Si* versus applied voltage at 83 V, the deflection of the membrane is 0.33 μ after that it is observed that the device is entering in collapse mode. From Fig. 8, it is observed that if the radius of the membrane is increased, the collapse voltage of the device decreases as well as if the thickness of membrane is decreased, the collapse voltage of the CMUT is decreases.

Figure 9 shows the CMUT hysteresis, it is also observed that for the given device, the collapse voltage is 83 V and

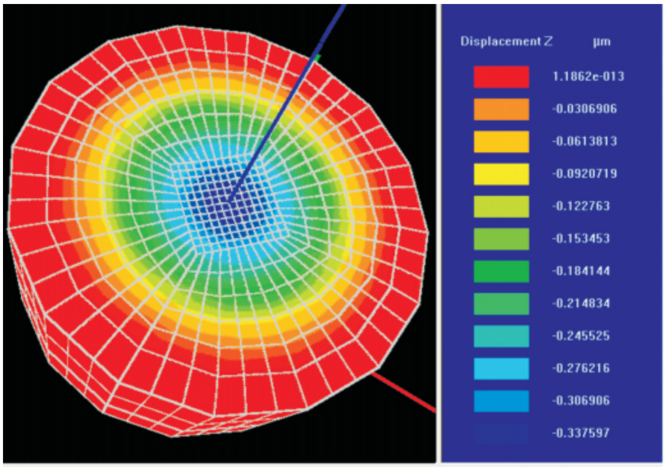


Figure 6. Displacement of the membrane at the collapse voltage.

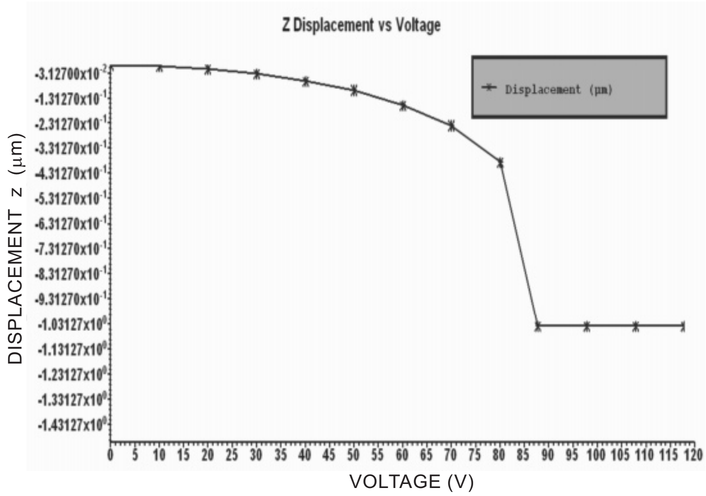


Figure 7. Plot of displacement versus voltage.

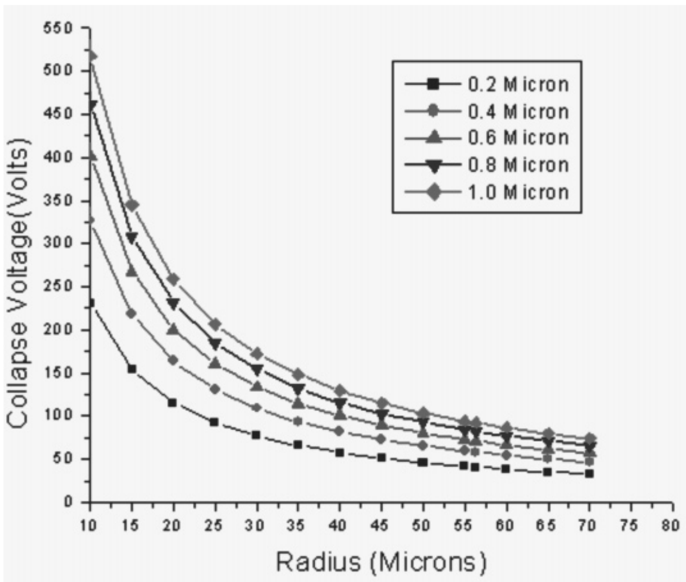


Figure 8. Collapse voltage versus radius of the membrane.

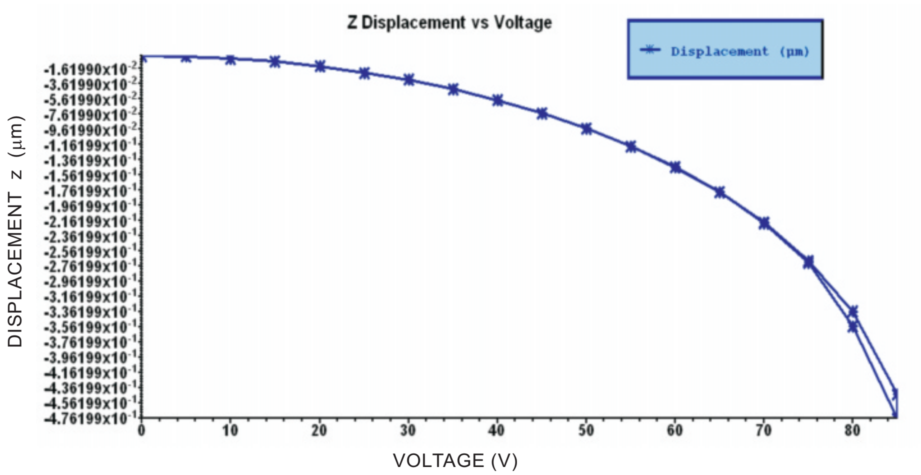


Figure 9. Voltage versus displacement of the membrane.

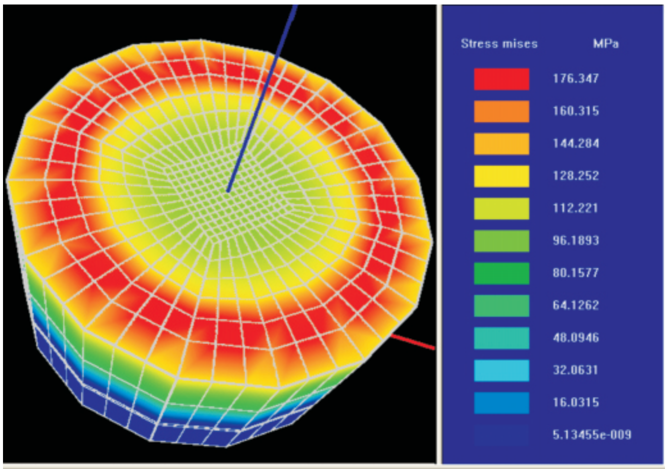


Figure 10. Pressure on the membrane due to collapse voltage.

snapback voltage is 74 V.

When voltage is applied between both plates of CMUT then maximum stress occurs at the edges of the membrane. For the 83 V of input FEM, simulated result for stress distribution of poly-*Si* membrane is given in Fig. 10.

From Fig. 11, it is observed that if voltage across the capacitor is increased, the capacitance increases nonlinearly, and after the collapse voltage, there is a sudden rise in capacitance. Ultrasonic waves were generated and received by two identical transducers. The signal was transmitted by biasing the transmitter transducer with a 50V dc bias as well as 10 V of ac signal. A resonant frequency of 1.3 MHz was used for the simulation of small signal equivalent circuit, as shown in Fig. 12.

7. CONCLUSIONS

The CMUTs have been an attractive alternative to piezoelectric transducers for some time, showing performance benefits such as an impedance match in air. In this paper the proposed device model is built using circular poly-*Si* membrane and from the results it is observed that the thickness of membrane affects collapse voltage, snapback voltage, and the natural frequency of the CMUT. It is further observed that the collapse voltage of the device decreases with increasing radius of the device and decreasing

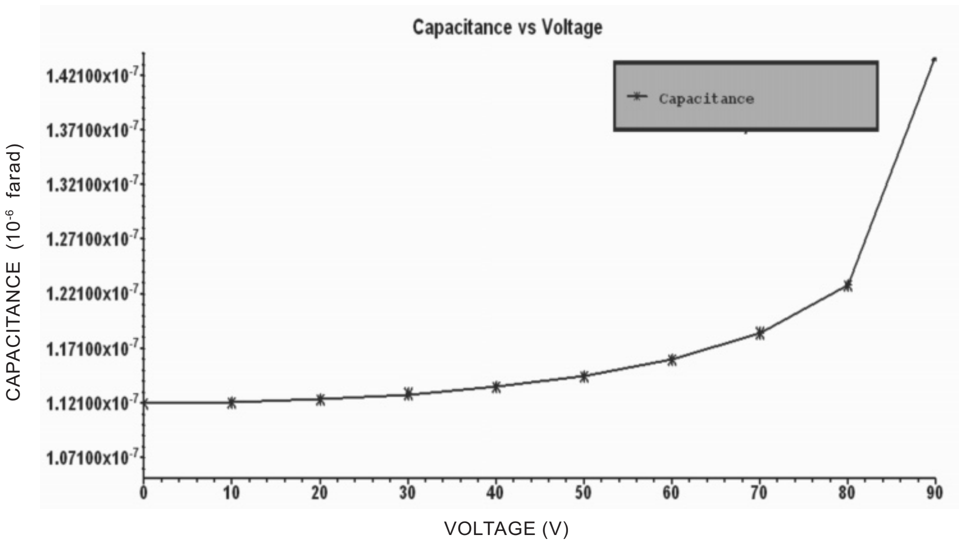


Figure 11. Capacitance versus voltage.

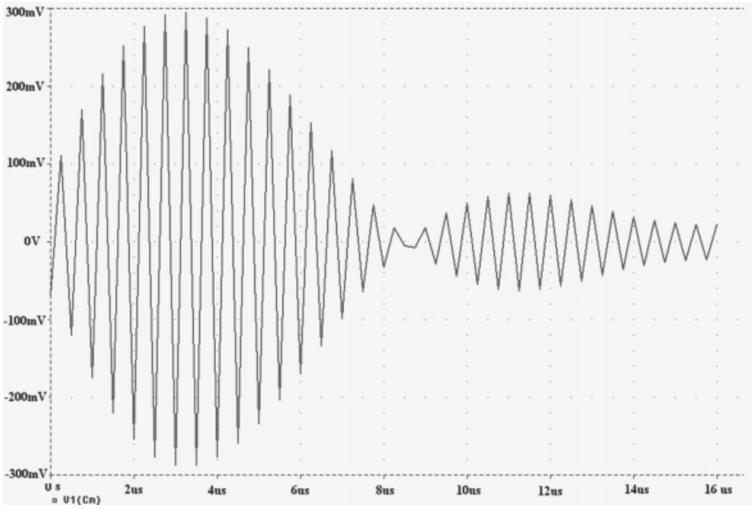


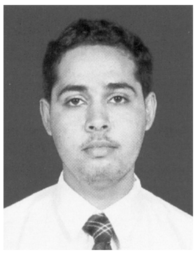
Figure 12. Transmitted ultrasonic signal.

thickness of the membrane. The best device performance was found to be at the resonance frequency.

REFERENCES

1. Cianci, E.; Foglietti, V.; Caliano, G. & Pappalardo, M. Micromachined capacitive ultrasonic transducer fabricated using silicon on insulator wafers. *Microelectronic Engineering*, 2002, **61-62**, 1025-029.
2. Ladabaum, Igal.; Soh, Hyongsok T. & Khuri Yakub, Butrus T. Surface micromachined capacitive ultrasonic transducer. *IEEE Trans. Ultrasonics, Ferroelect. Freq. Cont.,* May 1998, **45**(3).
3. Haller, Matthew I.& Khuri Yakub, Butrus T. A surface micromachined electrostatic ultrasonic air transducer. *IEEE Trans. Ultrasonincs, Ferroelect. Freq. Cont.,* January 1996, **43**(1).
4. Caliano, G. ; Galanello, F.; Caronti, A.; Carotenuto, R. & Pappalardo, M. Micromachined ultrasonic transducers using silicon nitride membrane fabricated in PECVD technology.
5. Ladabaum, Igal & Khuri Yakub, B.T. Micromachined ultrasonic transducers:11.4 MHz transmission in air and more. *Appl. Phy. Lett.*, 1998, **68**(1).
6. Mason, W.P. Electromechanical transducers and wave filters. Van Nostrand, New York, 1942.
7. Oralkan, Omer. ; Bayram, Baris.; Gosken, G.; Yaralioglu; Sanli Ergun; Kupnik, Mario.; Devid, T.; Yeh, Ira O. Wygant & KhuriYakub, B. T. Experimental characterisation of collapse mode CMUT operation. *IEEE Trans. Ultrasonics, Ferroelect. Freq. Cont.,* 2008, **53**(8), 1513-523.
8. Bozkurt, Ayhan.; Ladabaum, Igal.; Atalar, Abdullah & Khuri Yakub, B.T. Theory and analysis of electrode size optimisation for capacitive microfabricated ultrasonic transducers. *IEEE Trans. Ultrasonics, Ferroelect. Freq. Cont.,* 1999, **46**(6), 1364-374.
9. Huang, Yongli.; Sanli Ergun, A.; Haeggstrom, Edward. Badi, Mohammad H. & Khuri Yakub, B.T. Fabricating capacitive micromachined ultrasonic transducers with wafer-bonding technology. *J. Microelectromech. Sys.*, 2003, **12**(2),128-36.
10. Tiwari, Shailendra Kumar; Gopalkrishna Pai, A.; Arora, Anil; Satyanarayan, B.S. & Dwivedi, V.K. Influence of hexagonal shaped membrane thickness on the performance of capacitive micromachined ultrasonic transducers. *In* 2nd Institute of Smart Structure and Systems National Conference, CEERI, Pilani, 2007.

Contributors



Mr Shailendra Kumar Tiwari obtained his MTech (VLSI Design) from Sathyabama University, Chennai, and MSc (Electronics) from Gurughasi Das University, Bilaspur. Currently, he is teaching VLSI systems and RF-MEMS. His research interests are: MEMS and VLSI.

Prof B.S. Satyanarayana obtained his PhD (Electrical Engg) from Cambridge University, UK. He has worked in India and abroad with collaborators in Industry, R&D labs, and research institutions from UK, Japan, US, Korea, and Russia. He has over 50 research publications. His areas of research include: Nanotechnology, novel electronics material and devices, vacuum nanoelectronics, large area microelectronics and flexible electronics, flat panel displays, MEMS, networks and sensors and energy harvesting and energy conversion technologies.

Mr Gopalkrishna Pai obtained his BTech (Electronics and Communication Engg) from MIT, Manipal. Currently, he is teaching electronics circuits and analog communication in the Dept of Electronic and Communication Engg at the Manipal Institute of Technology, Manipal. His areas of research include MEMS and VLSI.

Mr Kunal K. Trivedi obtained his BE (Instrumentation Technology) from VTU in 2004. Since 2005, he is working as Applications Engineer at Bigtec Private Limited, Bangalore in the field of MEMS. His current research interests are: Modelling, simulation, design, and testing of MEMS, especially in space applications.